



Tribological Evaluation of Candidate Gear Materials Operating under Light Loads in Highly Humid Conditions

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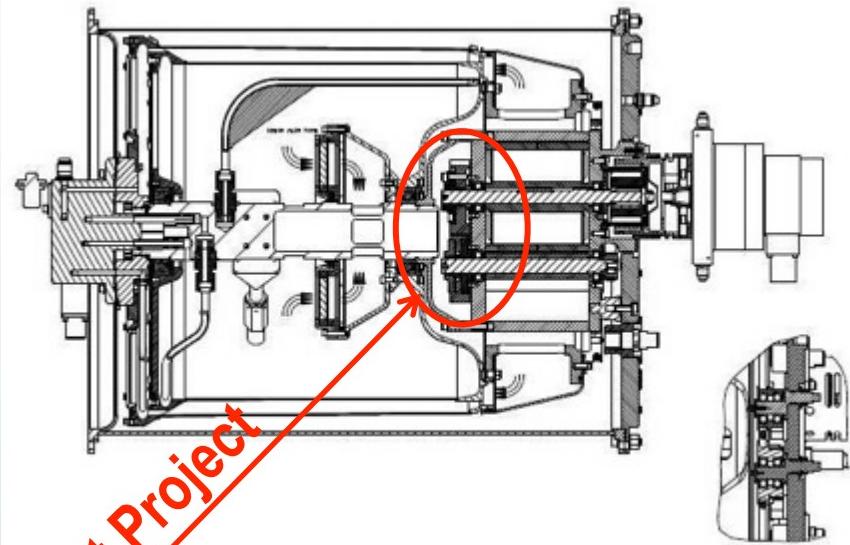


Opportunities: Superelastic Bearings and Gears

(ISS Wastewater purifier system offers technology “pull”)

- Required characteristics:
 - Impact load tolerance.
 - Intrinsic corrosion resistance (cannot rust)
 - High static load capability.
 - No toxic materials.
- ISS Urine Processor Pathfinder applications:
 - 50mm bore centrifuge bearings (wet, low speed, low load).
 - 12.7mm compressor bearings (moderate load, high speed, inaccessible location).
 - Compressor drive gears (dry lubed, damp, low load, high speed).

Earlier Investigations



Present Project

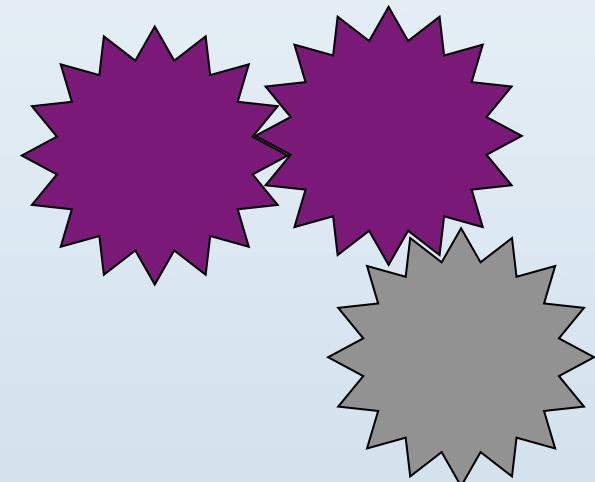
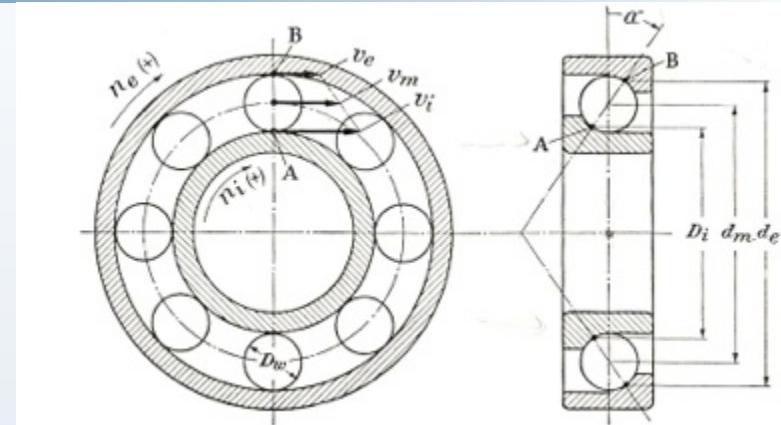
- Compressor Gears
 - Drives roots blower lobes.
 - 2000 rpm, high precision.
 - Moisture exposure.
 - Contacts process stream (must be non-toxic).



Technical Requirements:

(Material properties needed for bearings/gears)

- Bearing and gear materials must be:
 - Hard (Rockwell C58 or better)
 - Wear-resistant and compatible with existing lubricants
 - Resistant to fatigue (RCF)
 - Fracture resistant
 - Corrosion resistant (preferably immune)
 - Low density (to reduce centripetal loads at high rpm)
 - Capable of producing ultra-smooth surface finishes
 - Dimensionally stable and easy to manufacture





Mechanical Component Materials: State-of-Art (SOA)

(Current suite of candidates is severely limited)

- **Four general types of bearing and gear materials:**
 - Steels (Corrosion resistant steels, martensitic, austenitic)
 - Ceramics (Si_3N_4 balls + steel races, a.k.a., hybrid bearings)
 - Superalloys (e.g., jet turbine blade alloys)
 - Non-ferrous alloys (bronze, nylon etc.)
- **Each of these has inherent shortcomings:**
 - Hard steels are prone to rusting (even “stainless steels” like 440C)
 - Superalloys and austenitic stainless steels (304ss) are soft.
 - Ceramics have thermal expansion mismatch and dent steel races
 - Non-Ferrous materials are weak and lack temperature capabilities
- **No known bearing material blends all the desired attributes:**
 - High hardness, corrosion immunity, toughness, surface finish, electrical conductivity, non-magnetic, manufacturability, etc.



Superelastics: NiTi based intermetallics

(Hard but resilient material related to shape memory alloys)

- **60NiTi Basics: market name NiTiNOL 60**
 - W.J. Buehler invented NiTiNOL in the 1950's. Acronym for Ni-Ti-Naval-Ordnance-Laboratory.
 - 60NiTi (60 wt% Ni) is the baseline composition. Alloying with Hf, Zr, and Ta improves microstructure and processing.
 - 60NiTi is not a metal or a ceramic: a weakly ordered inter-metallic compound.
 - Closely related to the shape memory alloys, like NiTiNOL 55, but dimensionally stable.
 - 60NiTi is bearing hard (Rockwell C60) but only half as stiff as steel.
 - Brinell damage threshold load (pounds, kgf) is significantly (3-5X) higher than steel.



Highly polished 60NiTi bearing balls



60NiTi-Si₃N₄ Hybrid Bearing



Technical Properties Comparison:

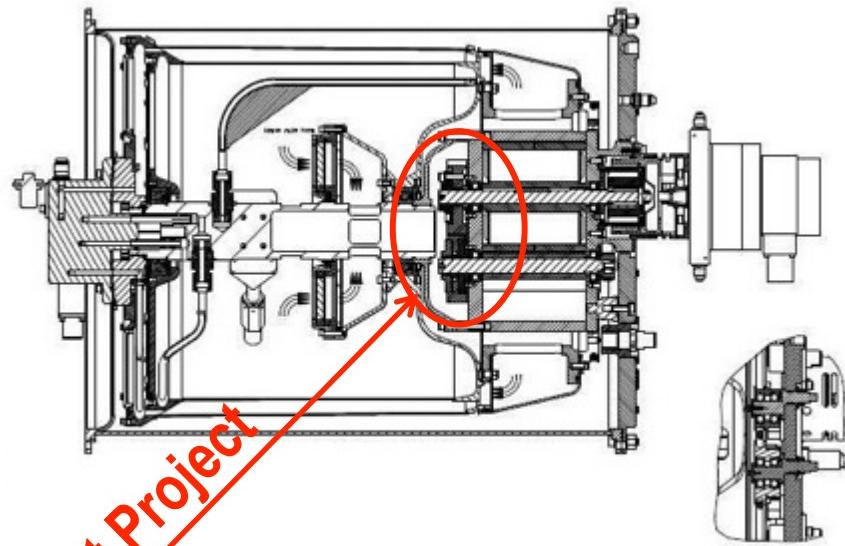
Property	60NiTi	440C	Si ₃ N ₄	M-50
Density	6.7 g/cc	7.7 g/cc	3.2 g/cc	8.0 g/cc
Hardness	56 to 62 HRC	58 to 62 HRC	1300 to 1500 Hv	60 to 65 HRC
Thermal conductivity W/m·°K	~9 to 14	24	33	~36
Thermal expansion	$\sim 11.2 \times 10^{-6} / ^\circ\text{C}$	$10 \times 10^{-6} / ^\circ\text{C}$	$2.6 \times 10^{-6} / ^\circ\text{C}$	$\sim 11 \times 10^{-6} / ^\circ\text{C}$
Magnetic	Non	Magnetic	Non	Magnetic
Corrosion resistance	Excellent (Aqueous and acidic)	Marginal	Excellent	Poor
Tensile/(Flexural strength)	~1000(1500) MPa	1900 MPa	(600 to 1200) MPa	2500 MPa
Young's Modulus	~95 GPa	200 GPa	310 GPa	210 GPa
Poisson's ratio	~0.34	0.3	0.27	0.30
Fracture toughness	~20 MPa/√m	22 MPa/√m	5 to 7 MPa/√m	20 to 23 MPa/√m
Maximum use temp	~400 °C	~400 °C	~1100 °C	~400 °C
Electrical resistivity	$\sim 1.04 \times 10^{-6} \Omega\text{-m}$	$\sim 0.60 \times 10^{-6} \Omega\text{-m}$	Insulator	$\sim 0.18 \times 10^{-6} \Omega\text{-m}$

- *Modulus is ½ that of steel, yet hardness is comparable.*
- *Tensile strength akin to ceramics.*
- *Does not rust. Enhanced static load capacity.*



Opportunities: Superelastic Bearings and Gears (ISS Wastewater purifier system offers technology “pull”)

- Superelastic enabling characteristics:
 - Impact load tolerance.
 - Intrinsic corrosion resistance (cannot rust)
 - High static load capability.
 - Non-magnetic but electrically conductive
 - Emerging manufacturing (M&P) database.
- ISS Urine Processor Pathfinder applications:
 - 50mm bore centrifuge bearings (wet, low speed, low load).
 - 12.7mm compressor bearings (moderate load, high speed, inaccessible location).
 - Compressor drive gears (dry lubed, damp, low load, high speed).



Present Project

- Compressor Gears
 - Drives roots blower lobes.
 - 2000 rpm, high precision.
 - Moisture exposure.
 - Contacts process stream (must be non-toxic).

Question #1: Can we make 60NiTi gears?



Gear Manufacturing: Multi-step process

- *Ingot: Hot Isostatic Press (HIP) of pre-alloyed powder*
 - *Wire EDM slice to gear thickness.*
 - *Take metallography samples for QC*
 - *Heat treat QC samples and verify hardness and microstructure*
 - *EDM drill wire starter holes.*
 - *Cut rough gear tooth shape.*
 - *Emerging manufacturing (M&P) database.*

60NiTi Ingot



60NiTi Ingot Slice



Wire Cut Blanks



*M&P-QC
Metallography*



*Microstructure and
quality verified.*



Method: Wire Electrode Discharge Machining (EDM)



Modern computer controlled (EDM) with gear tooth program



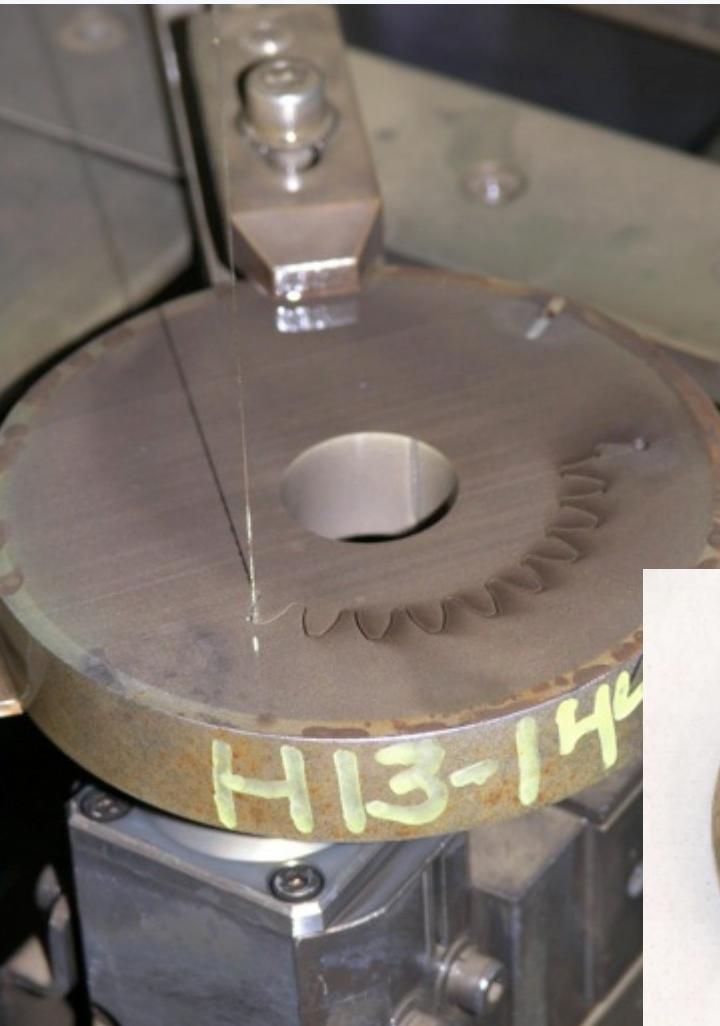
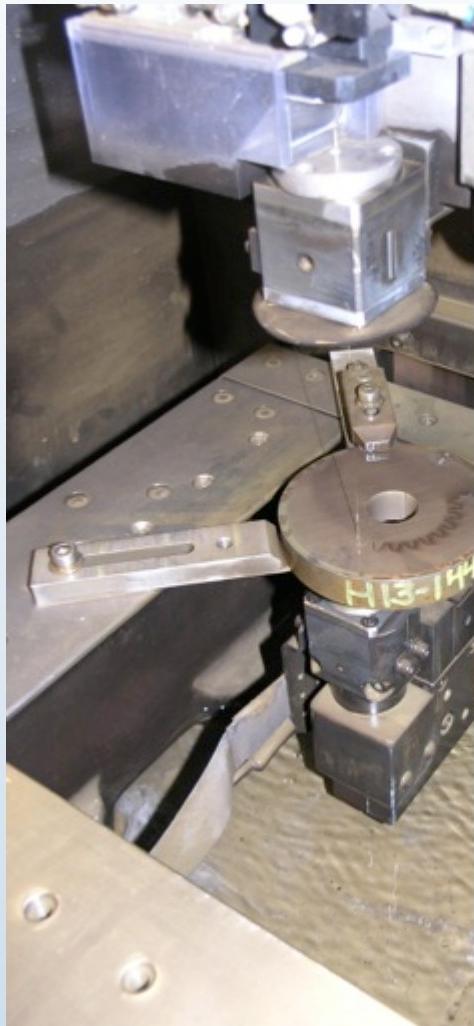
Water submerged electrode



Wire slowly moves through ingot slice like a cheese cutter

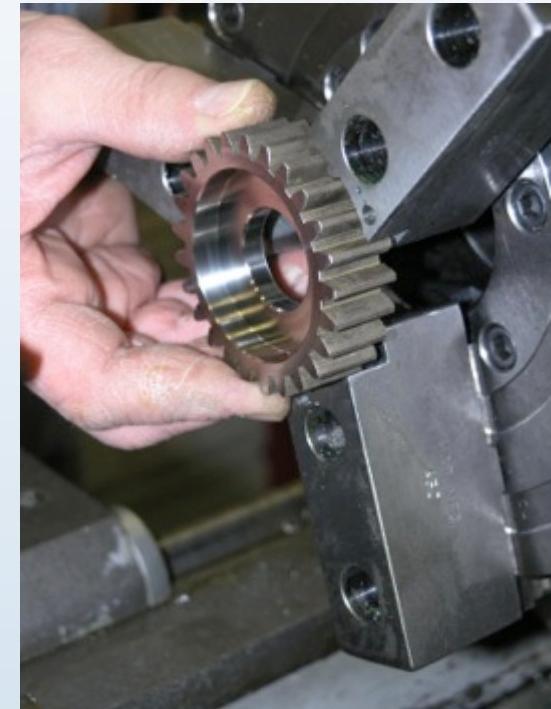
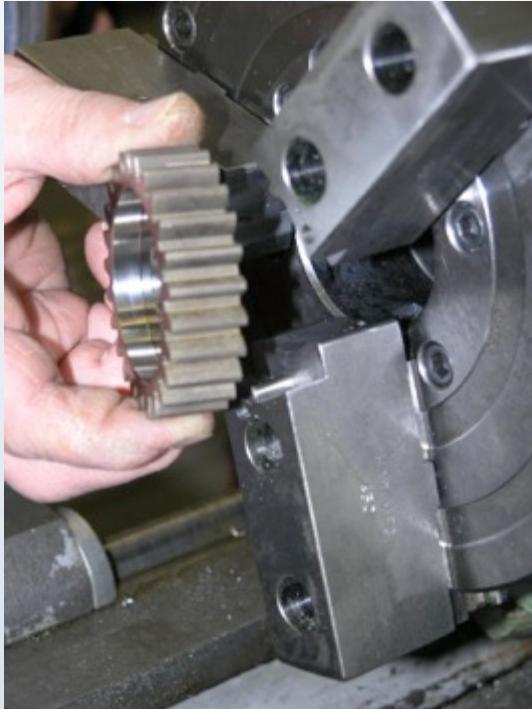
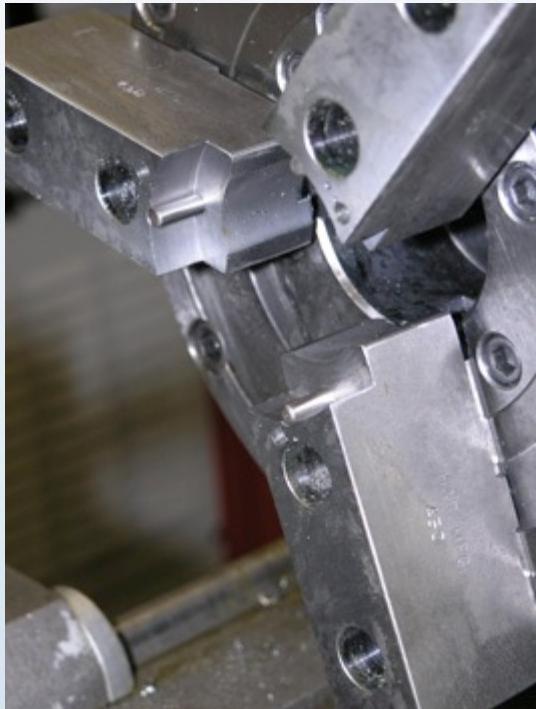


Method: Wire Electrode Discharge Machining (EDM)





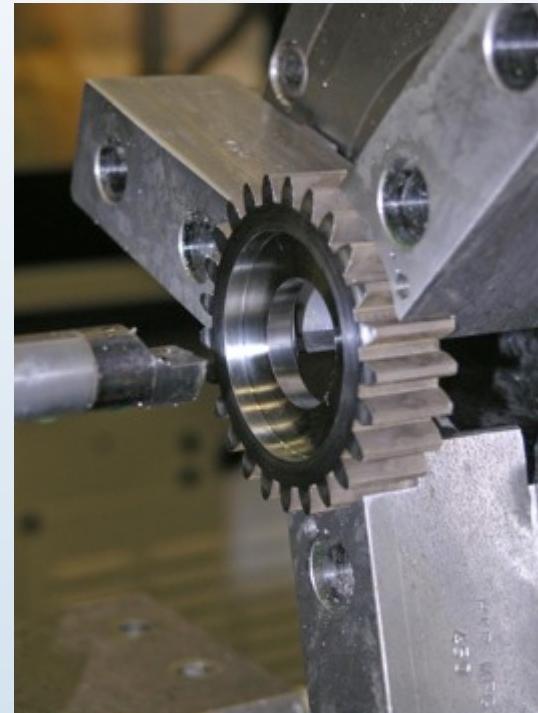
Turning: Carbide tool turning (lathe) to near finish dimensions





Fixtures: Lathe jaws machined in place to maximize accuracy

Approach: Jaw pins “between teeth” used to locate gear



Next Steps: Drill through holes and heat treat to harden.

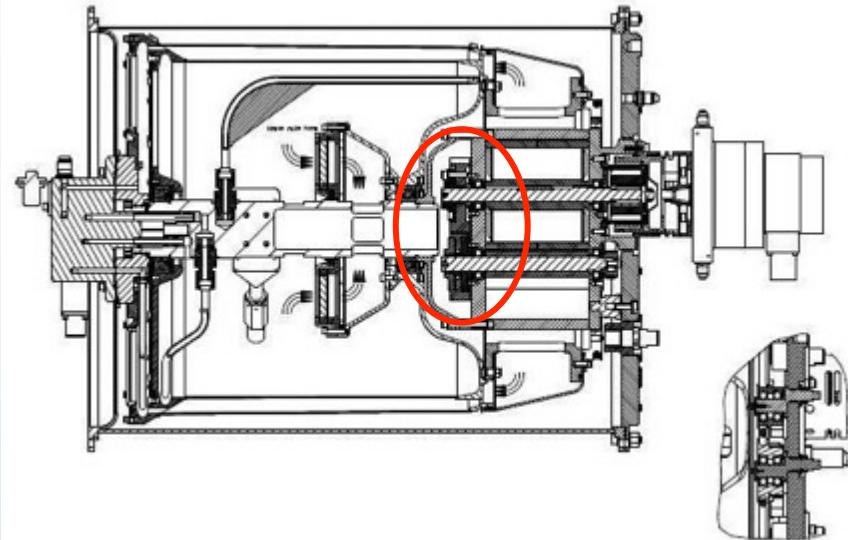
Question #2: Can we solid lubricate 60NiTi gears?



Challenges: Gear Problems

(Drive gears are life-limiting component)

- **Gear requirements:**
 - Run without oil & grease lubrication.
 - Withstand moist, acidic environment
 - High dimensional precision and stability.
 - Low wear, no toxic materials.
 - Baseline is stainless steel meshed with polyimide gear.
- **Approach:**
 - Simulate stainless-polyimide tooth mesh contact with pin-on-disk.
 - Evaluate 60NiTi as a hard, corrosion immune candidate gear material.
 - Establish feasibility of using dry film lubricant (DFL) to mitigate friction and wear.

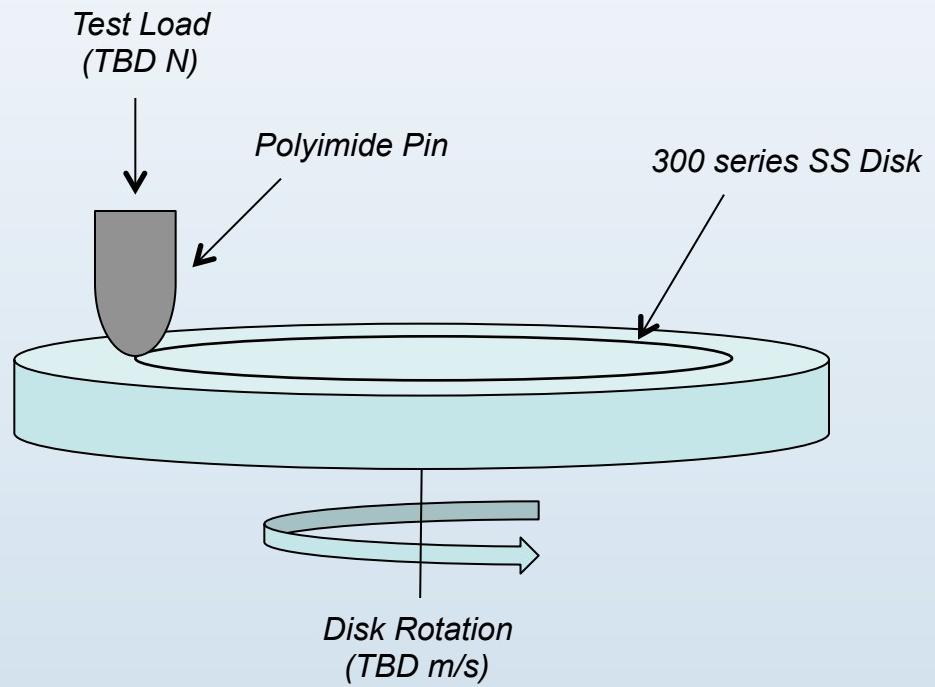
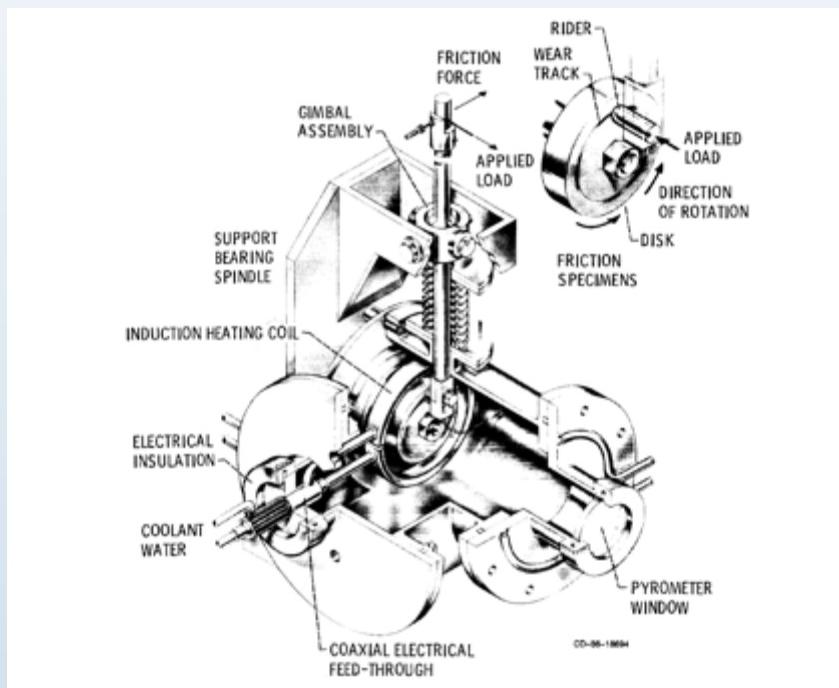


- **Compressor Gears**
 - *Drives roots blower lobes.*
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GEARS-Tribology Simulation

- Pin-on-disk sliding test designed to mimic gear tooth-tooth contact.
- Load and speed chosen to bracket gear application.
- Survey-type experiments done over range of load-speed combinations to find pair that produces wear surfaces that match worn Polyimide/SS gear surfaces.
- Data output: friction coefficient, pin wear factor {wear vol./($\text{load} \times \text{distance}$)}





Literature: Determine Tribology Test Conditions

Wear 309 (2014) 35–42
 Contents lists available at ScienceDirect
Wear
 journal homepage: www.elsevier.com/locate/wear



The wear of PEEK in rolling-sliding contact – Sim gear applications

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ABSTRACT

The wear and friction in the pitch region of the transition around this point of the tooth durability of polymer gear drives and car investigates the rolling-sliding wear behavior against each other with a simplified method high performance polymeric gear teeth.

Tests were conducted without external load disc test rig. The wear and friction mechanism in crystallinity correlating with the severity of also related to the structure of the contact surfaces.

Overall the PEEK discs were capable of running reduced with an increase of the sliding velocity due to the design process to allow the

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1. Introduction

With a growing awareness of engineering polymers, there is increasing application of polymers and polymeric composites to machine elements. The ability to economically manufacture and run unlubricated contacts at increasing temperatures (through the use of high temperature polymers such as poly-ether-ether-ketone (PEEK)) is making their application more desirable.

The majority of published work on the tribology and wear of non-conformal polymer pairs relates to the performance of gears. For a pair of gears the dominant operating parameters such as sliding velocity and load, and the geometric parameters such as module and curvature of the contacting surfaces vary with the contact position on the tooth profile. Consequently, gear action is a very complicated process to understand. An alternative method of studying gear action is to apply the same load and speed conditions to a much simpler geometry. An example of such a simulation is the use of two cylindrical discs loading against each other in edge-to-edge contact, each rotating at different speeds. By varying the relative speeds of the discs (i.e. changing the ratio of sliding to

rolling velocities) conditions estimated [1]. The difference however, differences it very different limited to areas throughout the

Nevertheless about material conformal contact was applied in order to a more fundamental rolling-sliding.

Previous work on the tribological properties of their compositions PA46 [3] PA66 [2,7,8], polyethylene (PT) PA66 [3]. The slip-ratio potential damage was for withstandings material was

It was found that the



Research Article

Lubrication Regimes in High-Performance Polymer Spur Gears

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 TRIBOLOGY

11

INFLUENCE OF A NON-STANDARD GEOMETRY OF PLASTIC GEAR ON SLIDING VELOCITIES

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ABSTRACT

In this paper the sliding velocities of plastic non-conventional spur gears is analysed. There are two peculiarities to be taken into account when metal gear practice is applied: the variable tooth height along the gear face width and the special meshing conditions of plastic gears. The study is based on the curved face width spur gear solid modelling which enable gear tooth geometry to be produced. A primary analysis shows the effect of the suggested spur gear design on the sliding velocity. Different curvatures and heights of the non-standard gear teeth show the influence of the tooth geometry on sliding velocity variation, a particular criteria for a further study on the optimisation of the gear geometry.

KEYWORDS: non-standard curved face width spur gear, plastic gear, sliding velocity

1. INTRODUCTION

Curved face width spur gears, with variable tooth height along the gear face width [1] are especially designed for plastic gears in order to increase their transmissible power level. The advantages of these gears, compared to standard spur gears are:

- higher contact ratio for a given size of gear and number of teeth;
 - lower bending and contact stresses;
 - better meshing in plane misalignment conditions;
 - no axial forces as are inherent in helical gears and enhanced lubrication under operating conditions.
- Against these advantages there are limitations:
- the difficulty in gear design due to the complex tooth geometry compared to conventional designs;
 - the difficulty in gear train mounting;
 - the sensitivity to center distance variations;
 - the manufacturer is limited to cutting processes, as designing a moulding die is almost impossible.

Experimental tests carried out by the authors on the running curved face width spur gears, with modified geometry, pointed out the peculiar thermal behavior of the non-standard gears [2]. With these non-standard gears, running at high loads, where conventional spur gears would fail, the gear surface temperature increased at an extremely high rate, recommending lubrication. It was obvious that the

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ars operating under lubricated conditions. An experimental and analytical HL under which polymer spur gears operate. In doing so theoretical film he regime according to Johnson's Map. The effects of lubrication on the ars were interpreted and from these results coefficients of friction were iry was investigated and the beneficial influence of high-pressure angle ocited with polymer gears the operating regime is shown to be mixed ested at high loads the operating regime became full film lubrication and

teeth come into contact. This deformation results in a change in the curvature of the gear tooth, increasing the contact area during tooth contact. Little has been published on externally lubricated polymer gears, the exception being Song et al. [5] who looked at polymer/steel combinations only and compared oil thicknesses and pressures with steel/steel pairs. They reported oil film thicknesses were higher for the polymer/steel combinations than for steel/steel pairs and that the maximum oil film pressure was lower for polymer/steel gears.

A programme of research was carried out in order to explore the potential of polymer gears made from a high performance material (PEEK) and also employing high pressure angle gears not normally used in metal/metal applications. In this paper the authors examined the different forms of elastohydrodynamic lubrication (EHL) and determined which category involute polymer gears fall under. Typical oil film thicknesses are determined and the effect these have on the performance of polymer/polymer and steel/polymer meshes were considered. Typical efficiencies were measured and from these curves, the operating coefficient of friction was determined. Finally, the effect of tooth geometry was examined and the beneficial influence of high tooth pressure angles was demonstrated.

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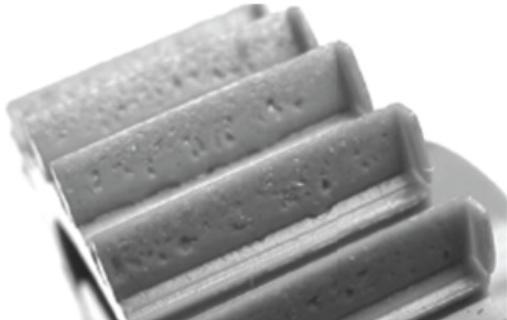
0043-1648 © 2013 The Authors. Published by Elsevier B.V. Open access under CCRV license
<http://dx.doi.org/10.1016/j.wear.2013.09.014>

*Three related papers offer analyses and equations to estimate sliding velocity and load.

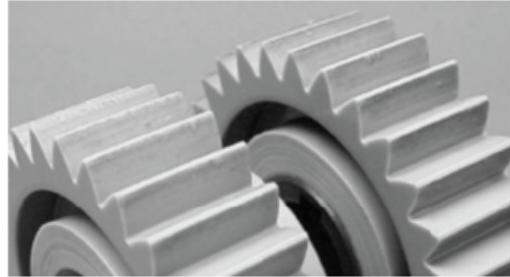


Literature: Determine Tribology Test Conditions

Advances in Tribology



(a)



(c)

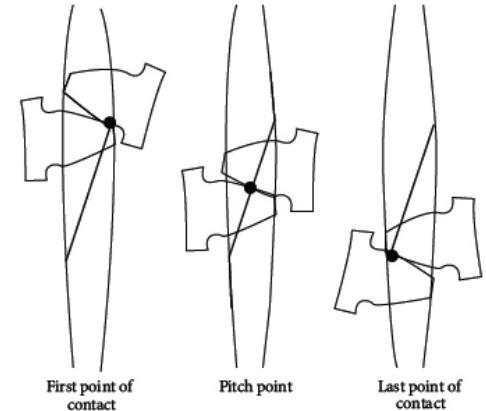
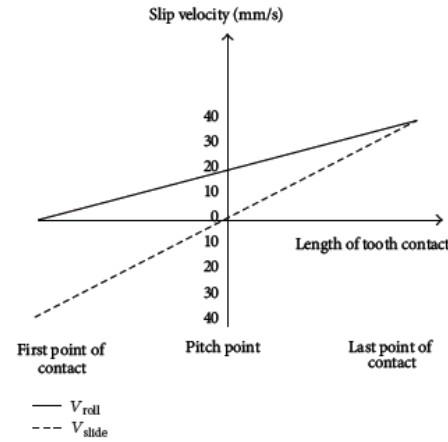


FIGURE 2: The line of contact and the rolling/sliding speeds along the contact path.

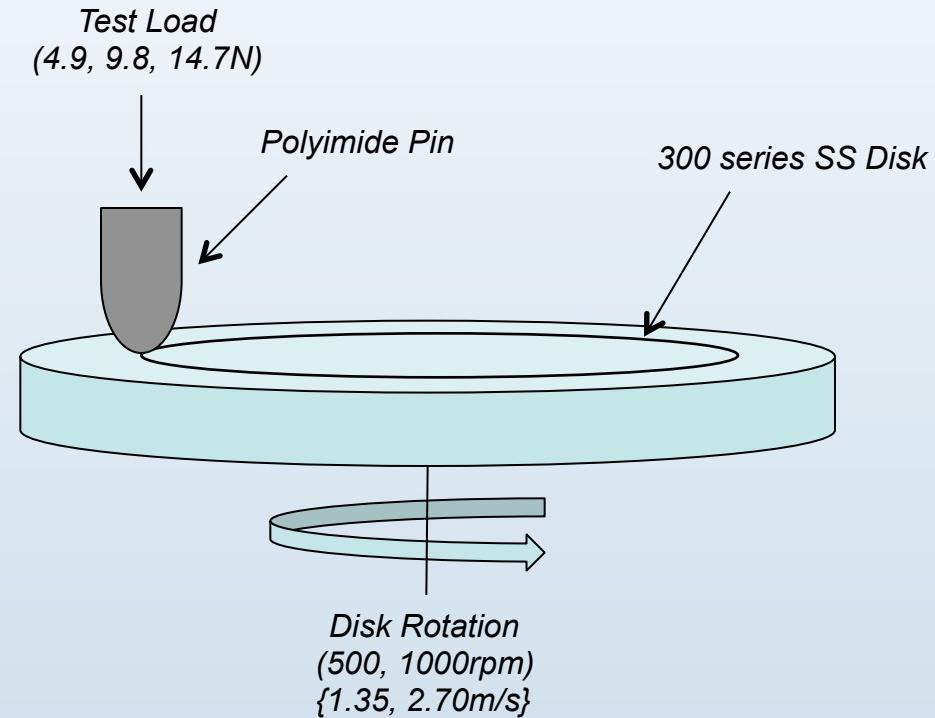
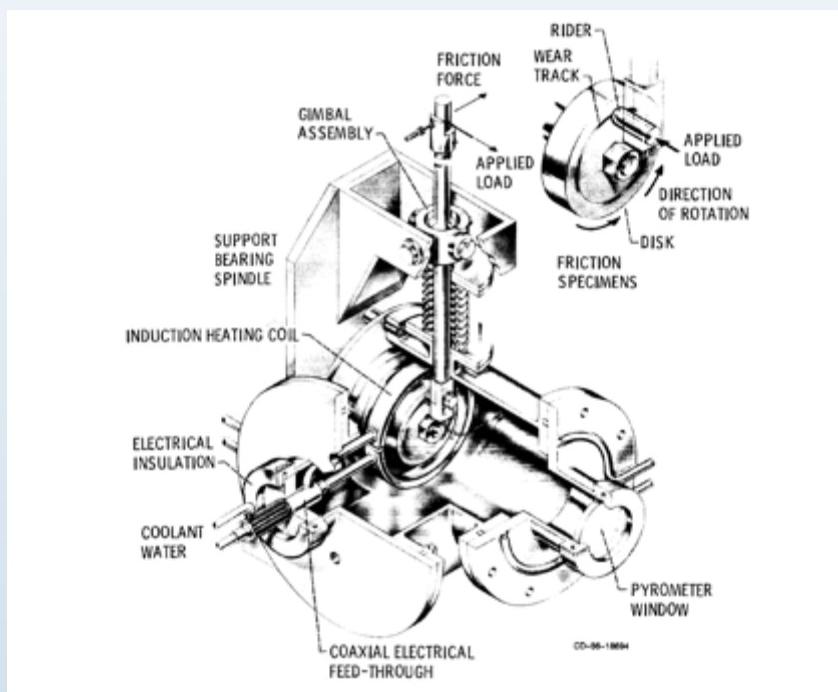
FIGURE 11: showing (a) a 20° pressure angle gear ran at 17 Nm, (b) the profile change over running time for the same gear, and (c) a pair of 30° pressure angle gears run at two different loads (17 Nm on the left and 22 Nm on the right).

*Selected sliding conditions: 4.9N load, 2.7m/s velocity



GEARS-Tribology Simulation

- Pin-on-disk sliding test designed to mimic gear tooth-tooth contact.
- Load and speed chosen to bracket gear application.
- Survey-type experiments done over range of load-speed combinations to find pair* that produces wear surfaces that match worn Polyimide/SS gear surfaces.
- Data output: friction coefficient, pin wear factor {wear vol./($\text{load} \times \text{distance}$)}



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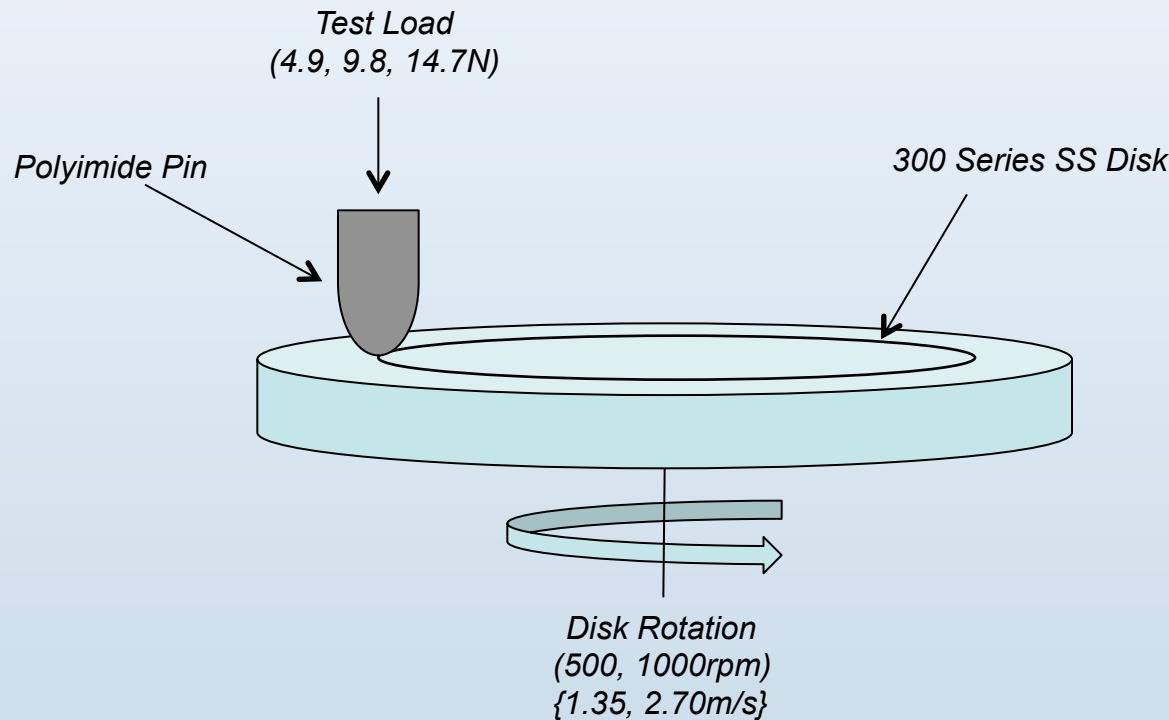


GEARS-Tribology Simulation

*Selected
sliding
conditions:
4.9N load,
2.7m/s velocity

Table I-Test Condition Evaluation-Friction and wear surface appearance
(Air at 25°C, 50-60% relative humidity)

Trial Load (N)	Trial Speed (m/s)	Friction Range	Surface Appearance
4.9	1.35	0.18-0.25	Smooth
4.9	2.70	0.25-0.36	Smooth
9.8	1.35	0.2-0.30	Rough to smooth
9.8	2.70	0.5-0.6	Rough
14.7	1.35	0.5-0.9	Rough
14.7	2.70	0.3-0.5	Rough

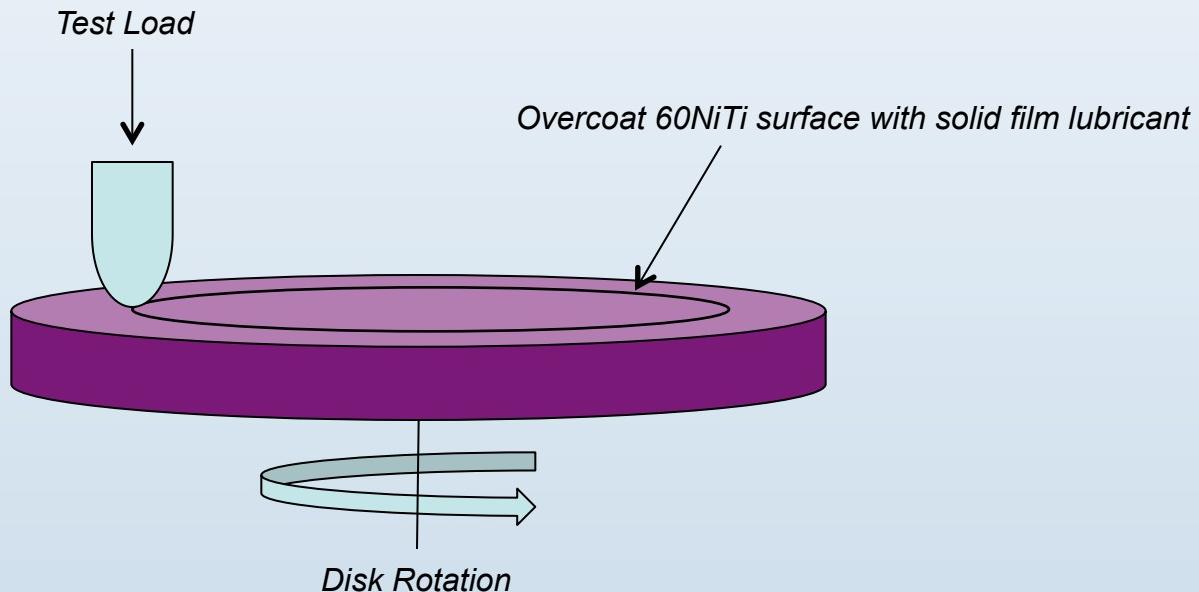




GEARS-Tribology Simulation for Dry Film Lubricant Coating

Solid Film Lubrication Concept

- Deposit special purpose dry film lubricant (DFL) onto gear teeth after grinding.
- Technique common practice in space mechanisms.
- Life must be determined through test.
- Use of non-galling gear materials (i.e., 60NiTi in place of 316SS) recommended.

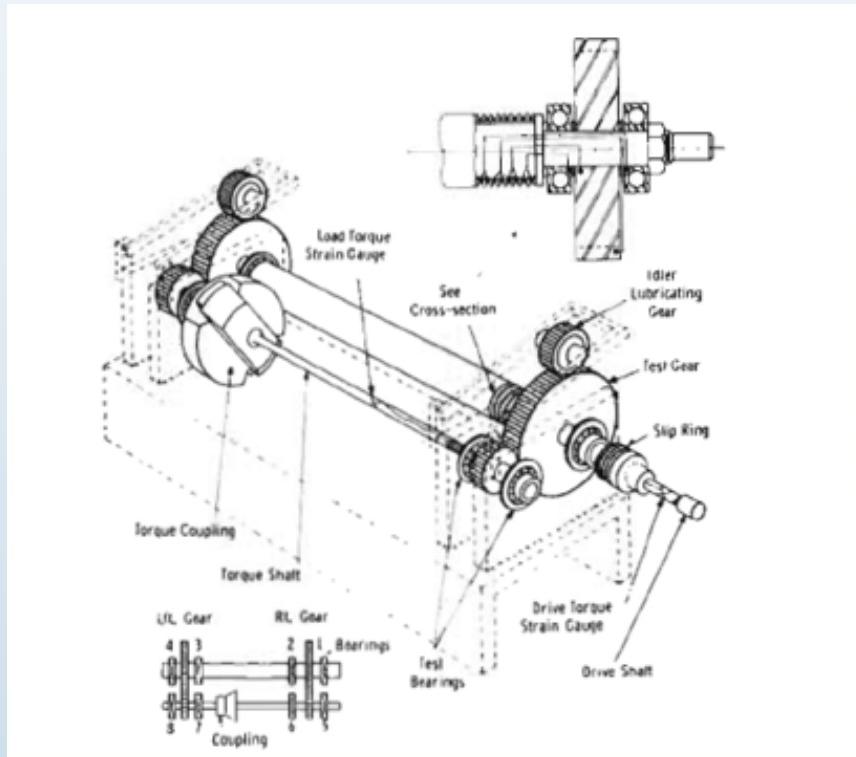




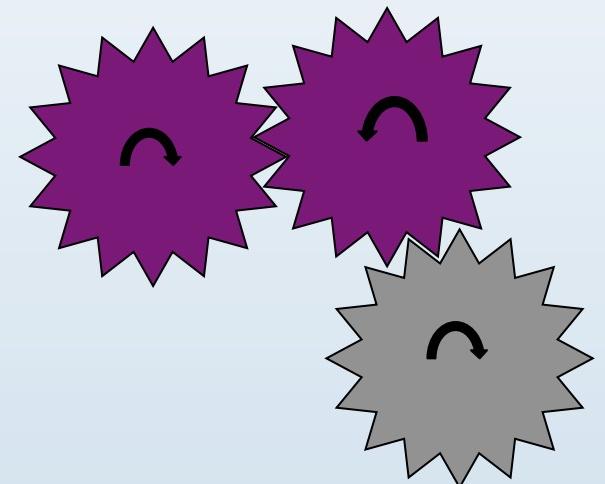
Transfer Film Lubrication: COMPRESSOR GEARS

Transfer Film Concept

- Polyimide idler gear to replenish DFL
- Added if DFL alone doesn't yield adequate gear life.



60NiTi Gears
(Coated with DFL)



Polyimide Idler Gear
(Lubricant Source)

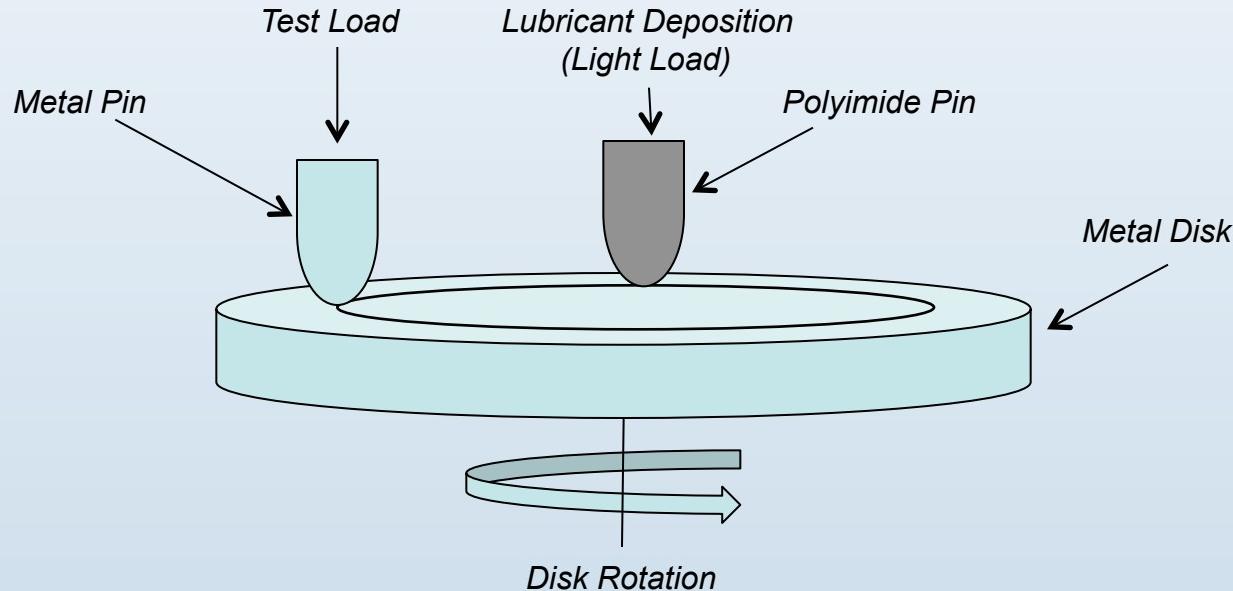
*1964 Bowen Paper shows idler gear lubrication



GEARS-Tribology Simulation

Transfer Film Solid Lubrication Concept

- Similar to bearing lubrication via transfer from the cage.
- Technique well described in early space mechanism literature but its current use is largely unknown.



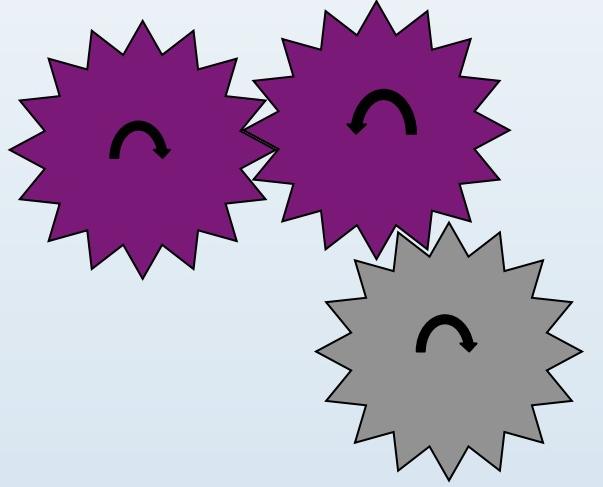


GEARS-Lubrication Systems Approach and Simulation

Transfer Film + Solid Lubrication Concept

Proposed Approach*:

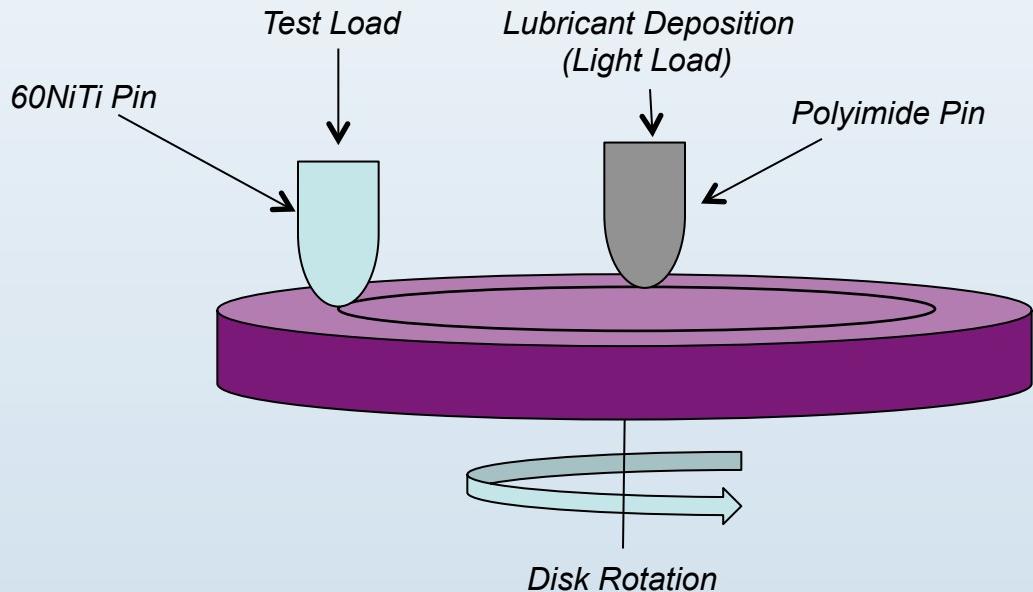
60NiTi Gear
(Coated with DFL)



Polyimide Idler Gear
(Lubricant Source)

Pin-on-Disk Simulation:

DFL coated 60NiTi Disk
(Polyimide transfer from pin)



*Polyimide idler gear proposed if DFL life proves inadequate.



GEARS-Tribology Data Summary

POD-Sliding Wear Results

Table II-Friction and Pin Wear Data Summary
(Test Conditions: 4.9N load, 2.7m/s sliding speed, air at 25°C)

Pin Material	Disk Material/Surface Coating	Friction Coefficient	Pin Wear Factor, mm ³ /N-m	Surface Appearance
SP21 Polyimide	316L SS	0.29 +/- 0.07	1.9 +/- 0.7 x 10 ⁻⁶	Smooth
SP21 Polyimide	304 SS	0.34 +/- 0.08	0.7 +/- 0.2 x 10 ⁻⁶	Smooth
SP21 Polyimide	60NiTi	0.28 +/- 0.04	2.1 +/- 1.5 x 10 ⁻⁶	Smooth
60NiTi	60NiTi	0.18 +/- 0.03	8.3 +/- 3.2 x 10 ⁻⁶	Rough
60NiTi + SP21	60NiTi	0.15 +/- 0.03	3.1 +/- 1.9 x 10 ⁻⁶	Smooth
60NiTi*	PTFE DFL	0.15 +/- 0.02	184-348 km**	Smooth
60NiTi*	Graphite DFL	0.17 +/- 0.02	24-135 km**	Smooth

*Tests initiated with pre-worn pin (~3mm dia. Wear scar).

**Tests terminated when DFL wore through to substrate. No additional pin wear was observed.



GEARS-Tribology Data Summary

Recommendation

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**Tests terminated when DFL wore through to substrate. No additional pin wear was observed.

Recommendation: 60NiTi gear set with PTFE-based DFL



Summary Remarks: Dry Lubed Gears

- Pin-on-disk testing was a rapid and convenient method to simulate polymer-metal gear tribology under lightly loaded conditions.
- Literature based models yielded test conditions that gave smooth tribo-surface characteristics representative of the target application.
- The polyimide material exhibited self-lubricating behavior in sliding against stainless steel and 60NiTi.
- PTFE based dry film lubricant coatings provided long-life, low friction performance superior to graphite based coatings but comparable to the polyimide.
- The use of a sacrificial polyimide slider for transfer film lubrication may be an effective means to replenish lubricant to the primary gear tooth surfaces.
- Full-scale gear tests are now needed to corroborate the pin-on-disk tests leading to an engineering decision point.



Thank You!